Transpower Seminar 2020

Optimising Reserve for Contingencies while Explicitly Including Response Speed of Reserve Providers

Josh Schipper

18 February 2020

Overview

- Motivation
- New Reserve Optimisation
- Compare New with Old Reserve Formulation
- Pricing Methodology

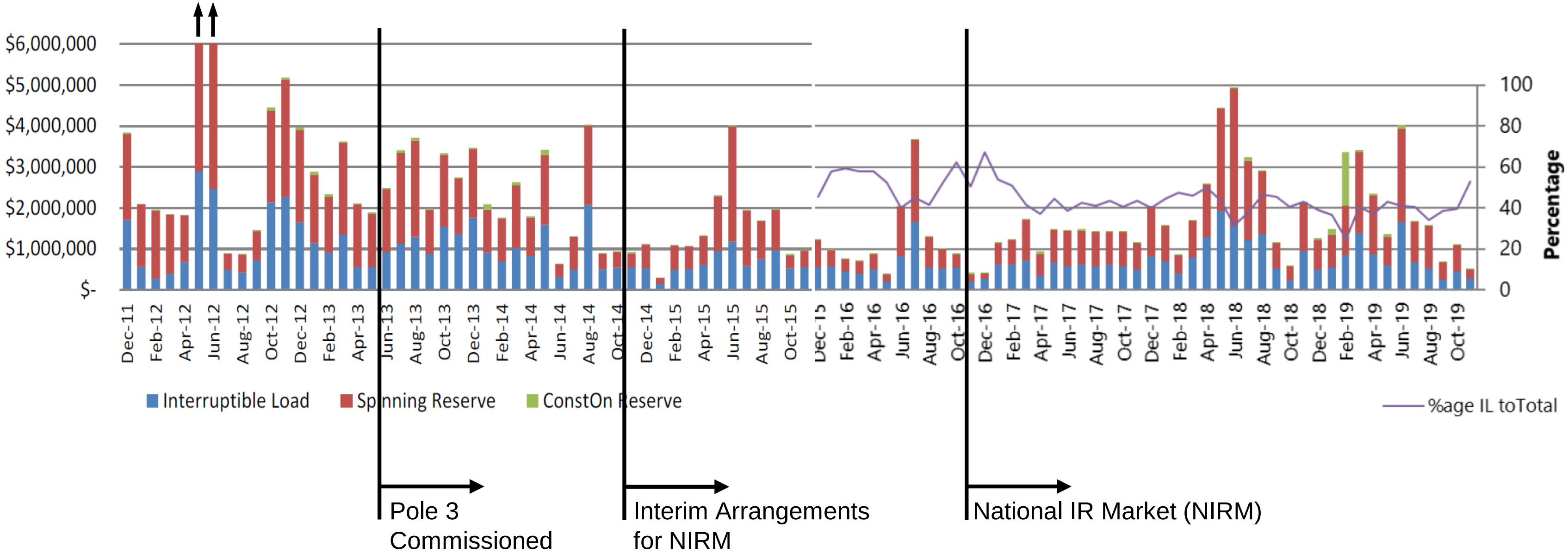
Why should the Instantaneous Reserve (IR) Market be modified?

Increasing awareness that

- Our ancillary services need to become 'technology agnostic' to allow the full value of emerging distributed energy resources to be realised through multiple products.

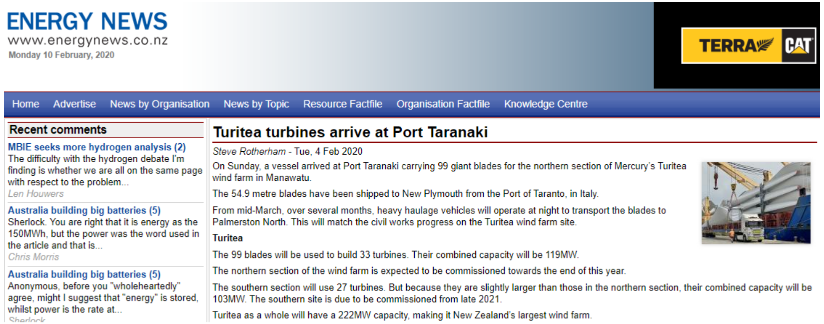
- And to consider the greater requirement for faster reserves to allow the greater uptake of intermittent wind and solar penetration.

Monthly Instantaneous Reserve Cost



Source: System Operator Monthly Performance Reports

More wind generation is coming …



ENERGY NEWS
www.energynews.co.nz
Monday 10 February, 2020

Home Advertise News by Organisation News by Topic Resource Factfile Organisation Factfile Knowledge Centre

Recent comments

MBIE seeks more hydrogen analysis (2)
The difficulty with the hydrogen debate I'm finding is whether we are all on the same page with respect to the problem...
Len Houwers

Australia building big batteries (5)
Sherlock. You are right that it is energy as the 150MWh, but the power was the word used in the article and that is...
Chris Morris

Australia building big batteries (5)
Anonymous, before you "wholeheartedly" agree, might I suggest that "energy" is stored, whilst power is the rate at...
Sherlock

Turitea turbines arrive at Port Taranaki

Steve Rotherham - Tue, 4 Feb 2020

On Sunday, a vessel arrived at Port Taranaki carrying 99 giant blades for the northern section of Mercury's Turitea wind farm in Manawatu.

The 54.9 metre blades have been shipped to New Plymouth from the Port of Taranto, in Italy.

From mid-March, over several months, heavy haulage vehicles will operate at night to transport the blades to Palmerston North. This will match the civil works progress on the Turitea wind farm site.

Turitea

The 99 blades will be used to build 33 turbines. Their combined capacity will be 119MW.

The northern section of the wind farm is expected to be commissioned towards the end of this year.

The southern section will use 27 turbines. But because they are slightly larger than those in the northern section, their combined capacity will be 103MW. The southern site is due to be commissioned from late 2021.

Turitea as a whole will have a 222MW capacity, making it New Zealand's largest wind farm.

Turitea Windfarm - 119 MW
Expected Completion – Late 2021

ENERGY NEWS
www.energynews.co.nz
Monday 10 February, 2020

Home Advertise News by Organisation News by Topic Resource Factfile Organisation Factfile Knowledge Centre

Recent comments

MBIE seeks more hydrogen analysis (2)
The difficulty with the hydrogen debate I'm finding is whether we are all on the same page with respect to the problem...
Len Houwers

Australia building big batteries (5)
Sherlock. You are right that it is energy as the 150MWh, but the power was the word used in the article and that is...
Chris Morris

Australia building big batteries (5)
Anonymous, before you "wholeheartedly" agree, might I suggest that "energy" is stored, whilst power is the rate at...
Sherlock

Australia building big batteries (5)

Waipipi construction starts

Craig Greaves - Fri, 1 Nov 2019

Tilt Renewables today marked the start of its Waipipi Wind Farm construction project with a sod turning ceremony at the South Taranaki site.

The $277 million project will see the installation of 31 turbines with 160 metre tip height - the largest ever mounted in New Zealand.

Tilt chief executive Deion Campbell says the 133 MW site is due to generate first energy late next year, with project completion set for March 2021. Melbourne-based Tilt expects Waipipi will generate about 455 GWh a year.

Construction is supported by a 20-year offtake agreement with Genesis Energy, under which the generator-retailer will purchase all of the farm's output.

"The power purchase agreement with Genesis secures our position as the only credible independent wind power developer in the country, with a great pipeline and the funding to deliver," says Campbell.

Waipipi is the first construction project Tilt has committed to in New Zealand, after the firm was formed in 2016 after a demerger of Trustpower's New Zealand and Australian wind generation assets and development rights.

"Having a project to build in our home country is important to us", Campbell says.

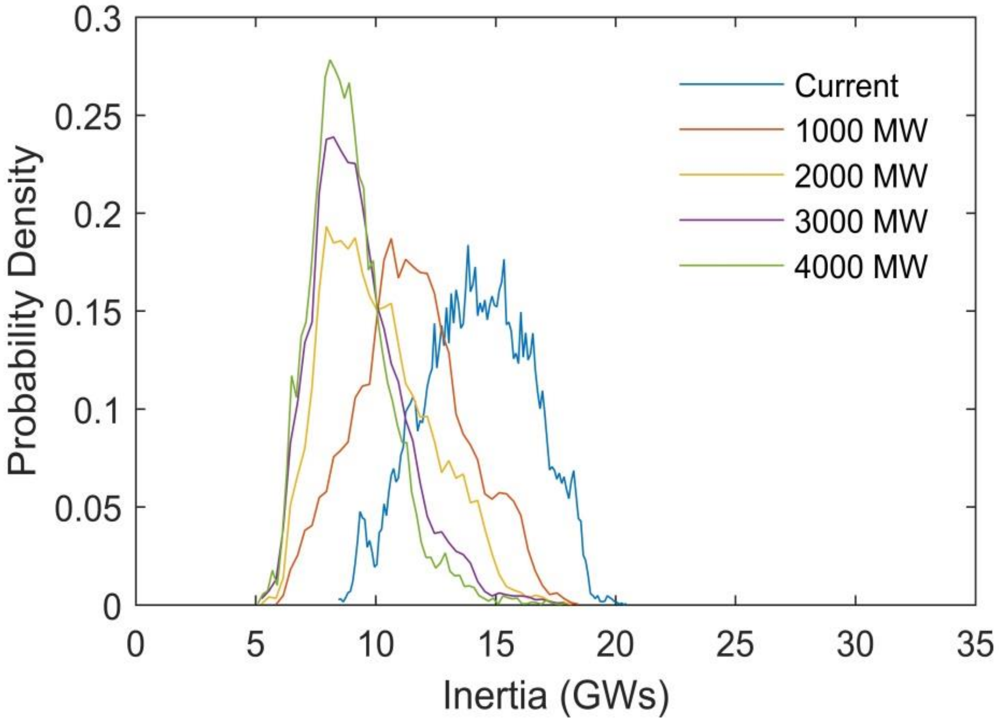
Waipipi Windfarm - 133 MW

… and will impact IR requirements.

- Reduced Inertia
  - If wind generation replaces thermal generation, North Island inertia will decrease.
  - In the South Island the minimum inertia will decrease, but the average will remain the same.

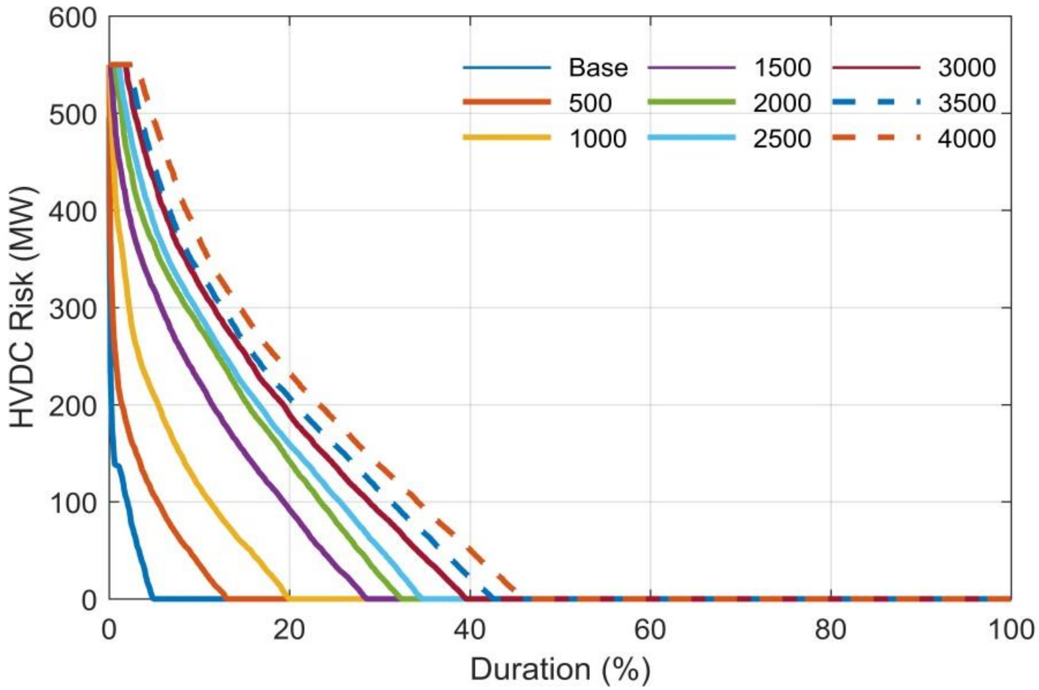
- Changes in Largest Risks
  - NI AC CE Risk will decrease, as large thermal units are removed from the NI.
  - NI DC CE Risk will increase, as HVDC transfers North will increase, assuming additional wind generation built in the SI.

Simulation of North Island Inertia



Scenarios of increasing wind generation in addition from the current 690 MW.

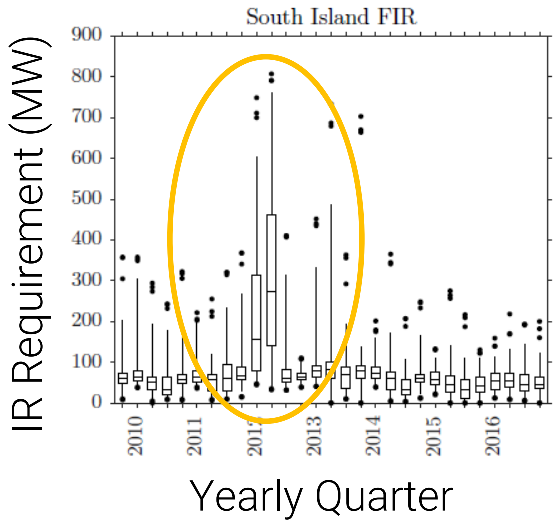
Simulation of NI DCCE Risk

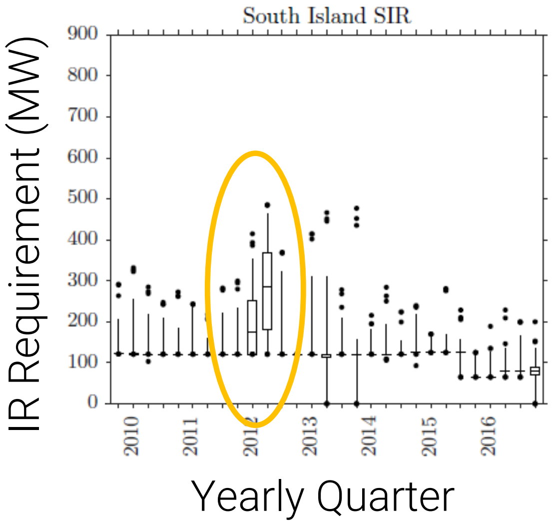


Scenarios of increasing wind generation in addition to the current 690 MW.

2012 South Island Reserve Shortage

Quarterly Distribution of IR Requirement





- Southward HVDC transfer
- SI with low inertia as there was low generation to conserve water.
- Greater requirement for FIR over SIR implying a greater requirement for the faster response speed.
- And that the frequency nadir would occur before 6 seconds.

Motivation - Questions

- Can ensuring response speed of reserve be more efficiently procured to avoid unused capacity?

- How can the different response speeds of Spinning Reserve (SR) and Interruptible Load (IL) be considered in the market optimisation and priced differently.

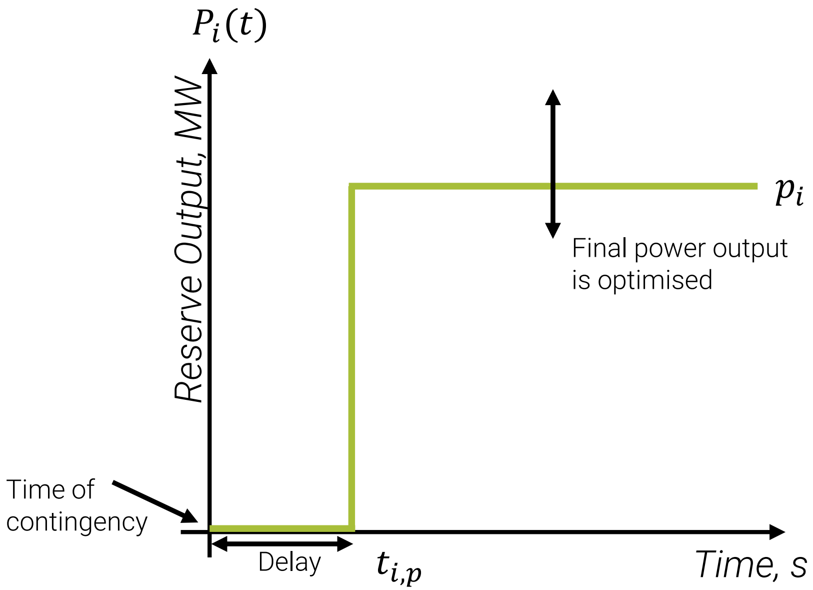
- Can other reserve types, such as Battery Energy Storage Systems (BESS) and synthetic inertia from wind turbines, participate in the IR market?

New Reserve Optimisation Formulation

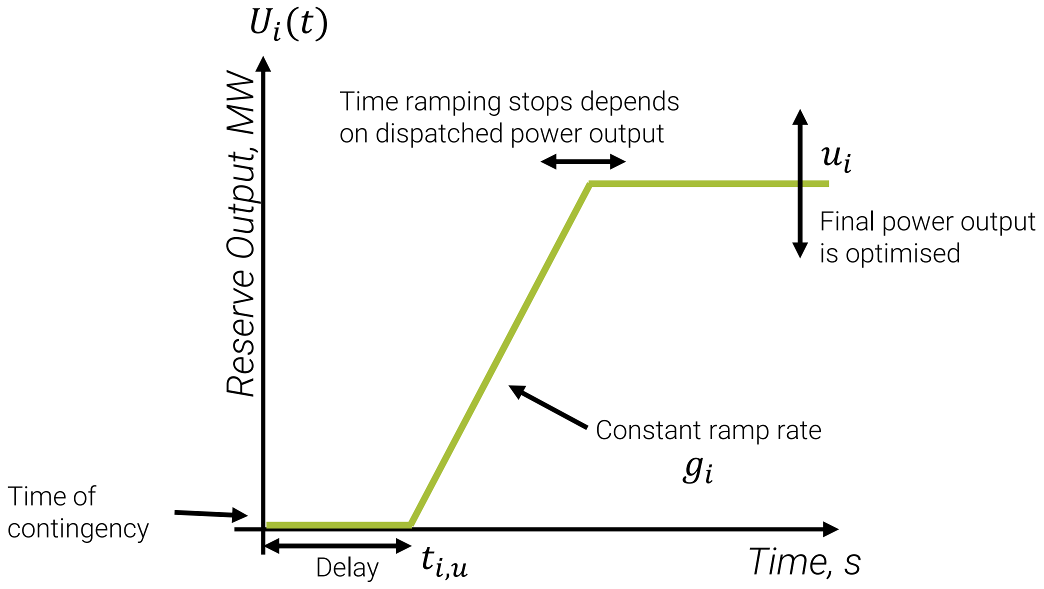
New Reserve Optimisation Formulation

- Similar to the Area Under the Curve (AUTC) approach.
- Avoids the discretisation of time that previous AUTC approaches require.
- Responses are modelled by two reserve categories, called:
  - Interruptible Load (IL) for an Instantaneous Response,
  - Spinning Reserve (SR) for a Ramped Response.
- Constraints on power system frequency are placed in the optimisation.

IL Offer – Instantaneous Response



SR offer – Ramped Response



Frequency Dynamics – Swing Equation

$$2H\frac{df}{dt} = -R + \sum_{i \in IL\_OFF} P_i(t) + \sum_{i \in SR\_OFF} U_i(t)$$

- f Power System Frequency transient in per unit deviation from the nominal frequency.
- H Inertial Constant in MWs.
- R Risk in MW.
- $P_i(t)$ Interruptible Load response as a function of time, in MW.
- $U_i(t)$ Spinning Reserve response as a function of time, in MW.
- i Index for each individual offer. IL_OFF is the set of IL offers, and SR_OFF is the set of SR offers.

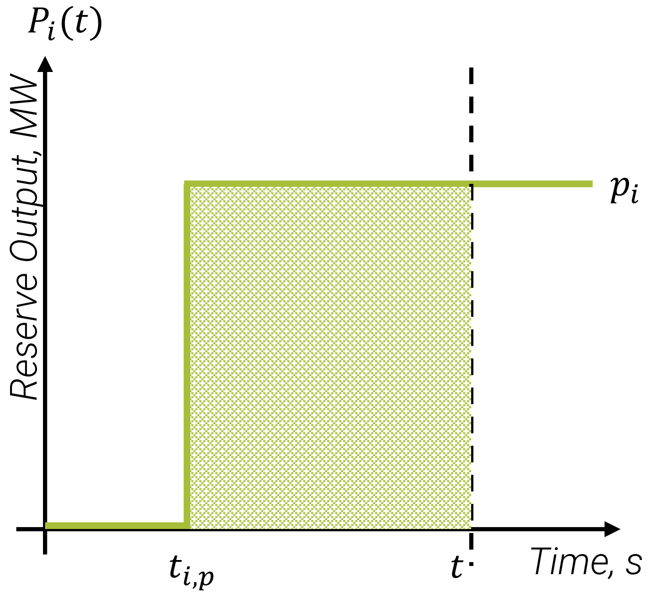
Integrating to find the Frequency Transient

$$2Hf(t) = \int_0^t -R + \sum_{i \in IL\_OFF} P_i(\tau) + \sum_{i \in SR\_OFF} U_i(\tau)\, d\tau + f(0)$$

- Integrating gives the meaning to why it is called an Area Under the Curve approach.
- It is assumed that the initial frequency is equal to the nominal value of 50 Hz, i.e. $f(0) = 0$.
- Partially evaluating the integral:

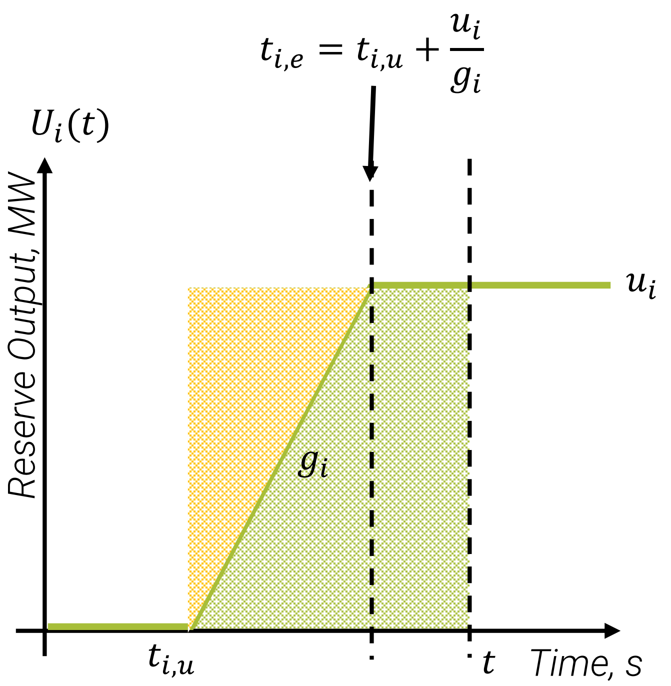
$$2Hf(t) = -Rt + \sum_{i \in IL\_OFF} \int_0^t P_i(\tau)\, d\tau + \sum_{i \in SR\_OFF} \int_0^t U_i(\tau)\, d\tau$$

Area Under an IL Offer



- For $t \leq t_{i,p}$ $\quad \int_0^t P_i(\tau)d\tau = 0$
- For $t \geq t_{i,p}$ $\quad \int_0^t P_i(\tau)d\tau = p_i \cdot (t - t_{i,p})$

Area Under an SR Offer



- Generally the area is equal to the area of the green rectangle minus the area of the orange triangle.
- For $t \le t_{i,u}$ $\quad \int_0^t U_i(\tau)d\tau = 0$
- For $t \ge t_{i,u}$ and $t \le t_{i,e}$

$$\int_0^t U_i(\tau)d\tau = U_i(t) \cdot (t - t_{i,u}) - \frac{U_i(t)^2}{2g_i}$$

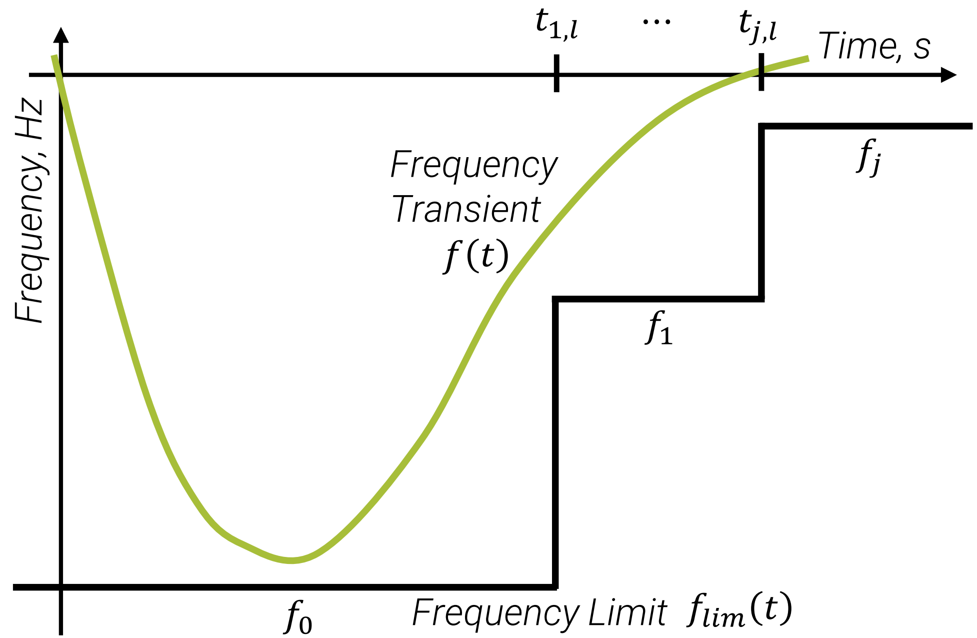
- For $t \ge t_{i,e}$

$$\int_0^t U_i(\tau)d\tau = u_i \cdot (t - t_{i,u}) - \frac{{u_i}^2}{2g_i}$$

Frequency Transient

$$2Hf(t) = -Rt + \sum_{\substack{t \geq t_{i,p} \\ i \in IL\_OFF}} p_i \cdot \left(t - t_{i,p}\right) + \sum_{\substack{t \geq t_{i,u} \\ i \in SR\_OFF}} U_i(t) \cdot \left(t - t_{i,u}\right) - \frac{U_i(t)^2}{2g_i}$$

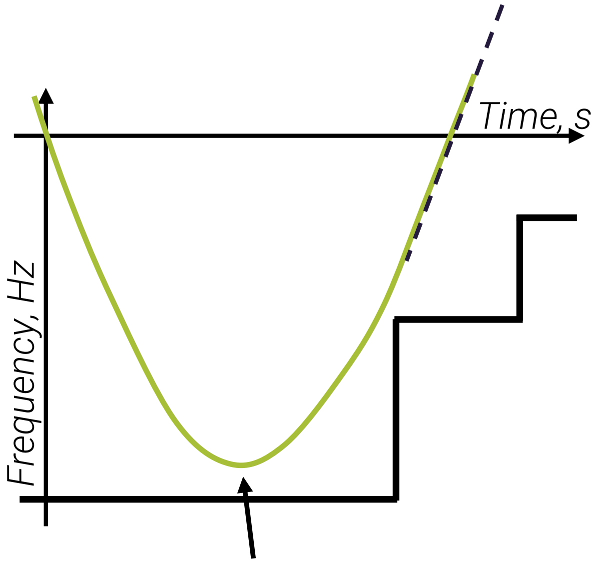
Frequency Limits



This optimisation forms a series of constraints to ensure that $f(t) \geq f_{lim}(t)$

Condition 1 – Reserve Requirement Constraint

Final gradient in the frequency transient is non-negative.

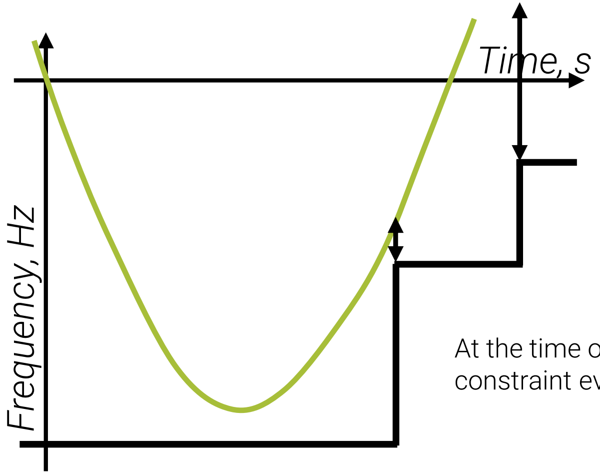


The exists of the minimum frequency is established.

$$R - \sum_{i \in IL\_OFF} p_i - \sum_{i \in SR\_OFF} u_i \leq 0$$

Reserve Requirement Constraint $R(\boldsymbol{v}) \leq 0$, where $\boldsymbol{v} = [H \quad R \quad p_1 \quad \cdots \quad u_1 \quad \cdots]^{\boldsymbol{T}}$

Condition 2 – Frequency Limits



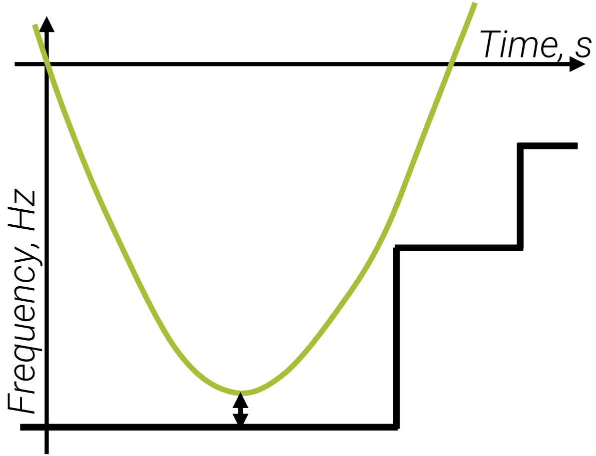
$$2Hf_k + Rt_{k,l} - \sum_{\substack{t_{k,l} \geq t_{i,p} \\ i \in IL\_OFF}} p_i \cdot (t_{k,l} - t_{i,p}) - \sum_{\substack{t_{k,l} \geq t_{i,u} \\ i \in SR\_OFF}} U_i(t_{k,l}) \cdot (t_{k,l} - t_{i,u}) - \frac{U_i(t_{k,l})^2}{2g_i} \leq 0$$

An individual constraint is called a frequency limit constraint, $F_k(\boldsymbol{v}) \leq 0$

At the time of each step change in frequency constraint evaluate $f(t) \geq f_{lim}(t)$

Condition 3 – Minimum Frequency Constraint

The time of the minimum frequency, t_{min}, occurs when $df/dt = 0$



The minimum frequency constraint requires $f(t_{min}) \geq f_{lim}(t_{min})$

$$2Hf_{lim}(t_{min}) + Rt_{min} - \sum_{\substack{t_{min} \geq t_{i,p} \\ i \in IL\_OFF}} p_i \cdot (t_{min} - t_{i,p}) - \sum_{\substack{t_{min} \geq t_{i,u} \\ i \in SR\_OFF}} U_i(t_{min}) \cdot (t_{min} - t_{i,u}) - \frac{U_i(t_{min})^2}{2g_i} \leq 0$$

The minimum frequency constraint is also expressed as, $F_{min}(\boldsymbol{v}) \leq 0$

Objective and Bounds

Objective

$$minimise \quad \sum_{i \in IL\_OFF} c_{i,p} p_i + \sum_{i \in SR\_OFF} c_{i,u} u_i$$

And Bounds

$$0 \le p_i \le p_i^{max}$$
$$0 \le u_i \le u_i^{max}$$

What are the difficulties?

1. The Frequency Limit Constraints, $F_k(\boldsymbol{v}) \leq 0$
   a. Quadratic term - $U_i(t_{k,l})^2/2g_i$
   b. The expression - $U_i(t_{k,l})$
2. The Minimum Frequency Constraint, $F_{min}(\boldsymbol{v}) \leq 0$
   a. The time of the minimum frequency t_{min} is a variable.
   b. Consequently the expression under the summation $t_{min} \geq t_{i,p}$ and $t_{min} \geq t_{i,u}$
   c. The expression $f_{lim}(t_{min})$

What does this mean for solving the problem?

- Cannot use Linear Programming (LP) or Quadratically Constrained Programming (QCP) to solve this problem.

How can it be solved?

- The feasible solution space is convex.
- The feasible solution space can be divided into finitely many QCP problems.
- A Piecewise QCP (PQCP) solver can be used.

Example of Dividing the Feasible Solution Space

- Removing $U_i(t_{k,l})$ from the frequency limit constraint …
- Divide the feasible solution space along the plane $u_i = g_i \cdot (t_{k,l} - t_{i,u})$

$$U_i(t_{k,l}) \cdot (t_{k,l} - t_{i,u}) - \frac{U_i(t_{k,l})^2}{2g_i} = u_i \cdot (t_{k,l} - t_{i,u}) - \frac{{u_i}^2}{2g_i}$$

$$U_i(t_{k,l}) \cdot (t_{k,l} - t_{i,u}) - \frac{U_i(t_{k,l})^2}{2g_i} = \frac{1}{2} g_i (t_{k,l} - t_{i,u})^2$$

Finishes ramping before $t_{j,l}$

Finishes ramping after $t_{j,l}$

u_i

$u_i = g_i \cdot (t_{k,l} - t_{i,u})$

Dispatch of Reserve from SR Offer i

General QCP problem for a region

$$\text{minimize} \quad \sum_i c_{i,p} p_i + \sum_i c_{i,u} u_i \tag{18}$$

$$\text{subject to} \quad p_m + \sum_{i \in Q_B} p_i + \sum_{i \in W_B} u_i + \sum_{i \in W_T} g_i (t_{min} - t_{i,u}) = R \tag{19}$$

$$p_m t_{min} + \sum_{i \in Q_B} p_i t_{i,p} + \sum_{i \in W_B} (u_i t_{i,u} + \frac{u_i^2}{2g_i}) + \sum_{i \in W_T} \frac{g_i}{2} (t_{min}^2 - t_{i,u}^2) \leq -2H f_{lim} \tag{20}$$

$$\forall j, \quad -R t_{j,l} + \sum_{i \in Q_{B,j}} p_i (t_{j,l} - t_{i,p}) + \sum_{i \in W_{B,j}} \left(u_i (t_{j,l} - t_{i,u}) - \frac{u_i^2}{2g_i} \right) + \sum_{i \in W_{T,j}} \frac{g_i}{2} (t_{j,l} - t_{i,u})^2 \geq 2H f_j \tag{21}$$

$$0 \leq p_m \leq \sum_{i \in Q_E} p_i \tag{22}$$

$$t_{min}^{min} \leq t_{min} \leq t_{min}^{max} \tag{23}$$

$$\forall i, \quad 0 \leq p_i \leq p_i^{max} \tag{24}$$

$$\forall i, \quad 0 \leq u_i \leq u_i^{max} \quad \text{or} \quad w_i^{min} \leq u_i \leq w_i^{max} \tag{25}$$

Notes to the previous slide

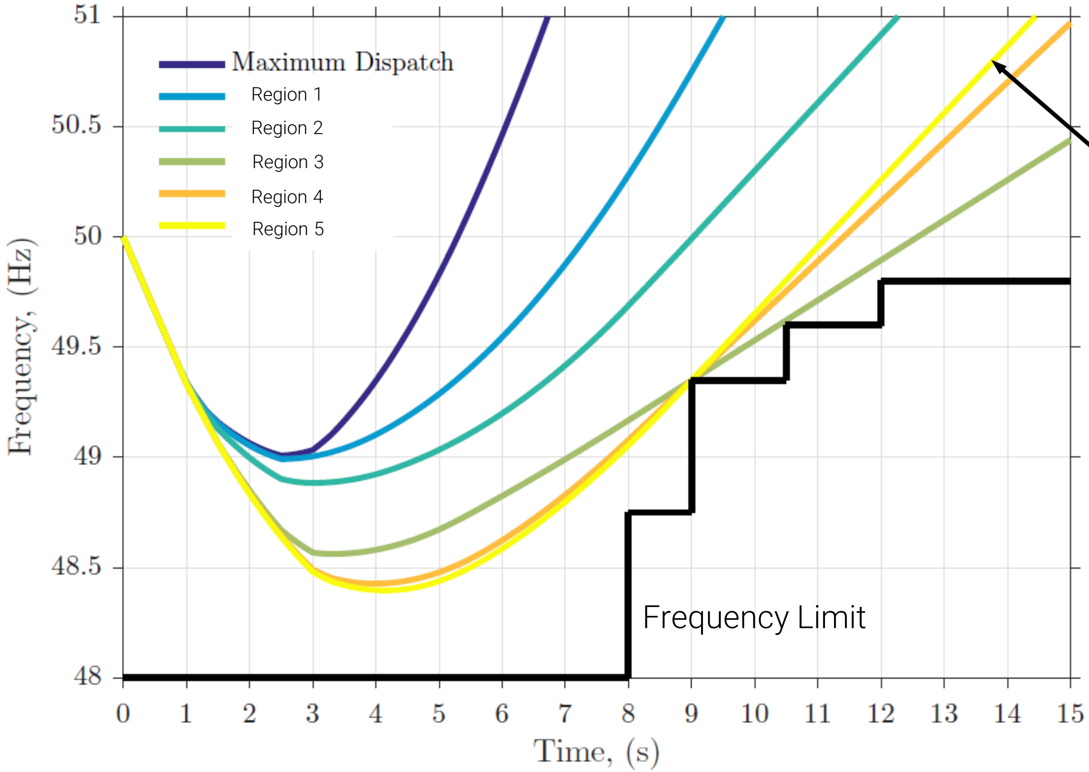
- For an IL type region p_m is a variable, t_{min} is constant, and (23) is removed.
- For a SR type region t_{min} is a variable, $p_m = 0$, and (22) is removed.
- p_m is the IL reserve offered at the minimum time, t_{min}, in order to satisfy the reserve requirement, (19). This value cannot be greater than the amount dispatched at the minimum time, (22), where the set Q_E is all the IL offers, $t_{i,p} = t_{min}$.
- Q_B, set of IL offers initiated before the minimum time, $t_{i,p} < t_{min}$.
- W_B, set of SR offers that finishes ramping before the minimum time, $t_{i,u} < t_{min}$ and $t_{i,u} + u_i/g_i \leq t_{min}$. The latter of these conditions is expressed in (25) as $w_i^{max} = g_i(t_{min} - t_{i,u})$.
- W_T, the set of SR offers that continue ramping past the minimum time, $t_{i,u} < t_{min}$ and $t_{min} \leq t_{i,u} + u_i/g_i$. In (25), $w_i^{min} = g_i(t_{min} - t_{i,u})$. For a SR type region, W_T is required to have at least one element. This is to ensure the definition of t_{min} by (19) so that the condition of (8) and (9) is satisfied.
- In the minimum frequency constraint, (20), the frequency limit is found, $f_{lim} = f_{lim}(t_{min})$. The frequency level, $f_k = f_{lim}$, if $k > 1$ then the frequency limit constraints for $j < k$ in (21) are not required. These constraints will be satisfied regardless.
- The term $p_m t_{min}$ would generally imply (20) not to be a convex constraint. For IL or SR type regions either t_{min} or p_m is constant, therefore (20) is convex.
- $Q_{B,j}$, set of IL offers initiated before the step change in frequency limit, $t_{i,p} < t_{j,l}$.
- $W_{B,j}$, set of SR offers that stop ramping before the step change, $t_{i,u} < t_{j,l}$ and $t_{i,u} + u_i/g_i \leq t_{j,l}$. In (25), $w_i^{max} = g_i(t_{j,l} - t_{i,u})$.
- $W_{T,j}$ set of SR offers that continue ramping past the step change, $t_{i,u} < t_{j,l}$ and $t_{j,l} \leq t_{i,u} + u_i/g_i$. In (25), $w_i^{min} = g_i(t_{j,l} - t_{i,u})$.
- The constants t_{min}^{min} and t_{min}^{max} can be either $t_{j,l}$, $t_{i,p}$, $t_{i,u}$, or $t_{i,e}^{max}$ depending on the region chosen.

Example 1 - Offers

TABLE I
LIST OF IL AND SR OFFERS FOR THE FIRST EXAMPLE

	Quantity (MW)	Price ($/MW)	$t_{i,p}/t_{i,u}$ (s)	g_i (MW/s)
		IL Offers		
1	10	150	0.9	-
2	38	126	0.9	-
3	16	0	1	-
4	57	65	1	-
5	42	132	1.1	-
6	63	118	1.3	-
7	29	98	1.5	-
8	50	100	2.5	-
9	75	50	3	-
10	18	20	3.3	-
		SR Offers		
1	90	80	1.2	15
2	32	160	1.3	8
3	10	100	1.3	2
4	200	5	1.4	25
5	62	0	1.4	15
6	25	10	1.5	5
7	56	40	1.5	6
8	81	50	1.6	12
9	8	84	1.7	1
10	27	18	2	6

Example 1 – Optimal Frequency Transient



Frequency Transient with the optimum price

Inertia is 15,000 MWs
Risk is 400 MW

Example 1 – Global Optimum

Solutions after solving each region/step

	Region 1	Region 2	Region 3	Region 4	Region 5
	IL Dispatch (MW)				
1	3.9	0	0	0	0
2	38	38	0	0	0
3	16	16	16	16	16
4	57	57	57	57	57
5	42	12	0	0	0
6	63	63	11.9	0	0
7	29	29	29	29	25.83
8	50	50	50	0	0
9	0	0	75	75	75
10	0	0	0	18	18
	SR Dispatch (MW)				
1	19.5	27	31.5	31.91	25.16
2	9.6	0	0	0	0
3	2.4	3.4	4	1.55	0.09
4	190	165	94.78	165	180.43
5	39.25	43	62	62	62
6	5	7.5	9	12.35	25
7	54	45	39	29.96	26.63
8	76.8	16.8	20.4	51.19	42.88
9	7.3	6.3	1.6	1.38	0.87
10	3	6	7.8	11.81	27
	Total Dispatched Reserve (MW)				
	705.75	585	508.98	562.15	581.90
	Total Cost ($)				
	40,901	32,030	23,040	18,399	17,289

Offers

Quantity (MW)	Price ($/MW)	$t_{i,p}/t_{i,u}$ (s)	g_i (MW/s)
IL Offers			
10	150	0.9	-
38	126	0.9	-
16	0	1	-
57	65	1	-
42	132	1.1	-
63	118	1.3	-
29	98	1.5	-
50	100	2.5	-
75	50	3	-
18	20	3.3	-
SR Offers			
90	80	1.2	15
32	160	1.3	8
10	100	1.3	2
200	5	1.4	25
62	0	1.4	15
25	10	1.5	5
56	40	1.5	6
81	50	1.6	12
8	84	1.7	1
27	18	2	6

Optimal Dispatch

Impact of Inertia and Risk on the Optimal Dispatch

Example 2 - Offers

LIST OF IL AND SR OFFERS FOR THE SECOND EXAMPLE

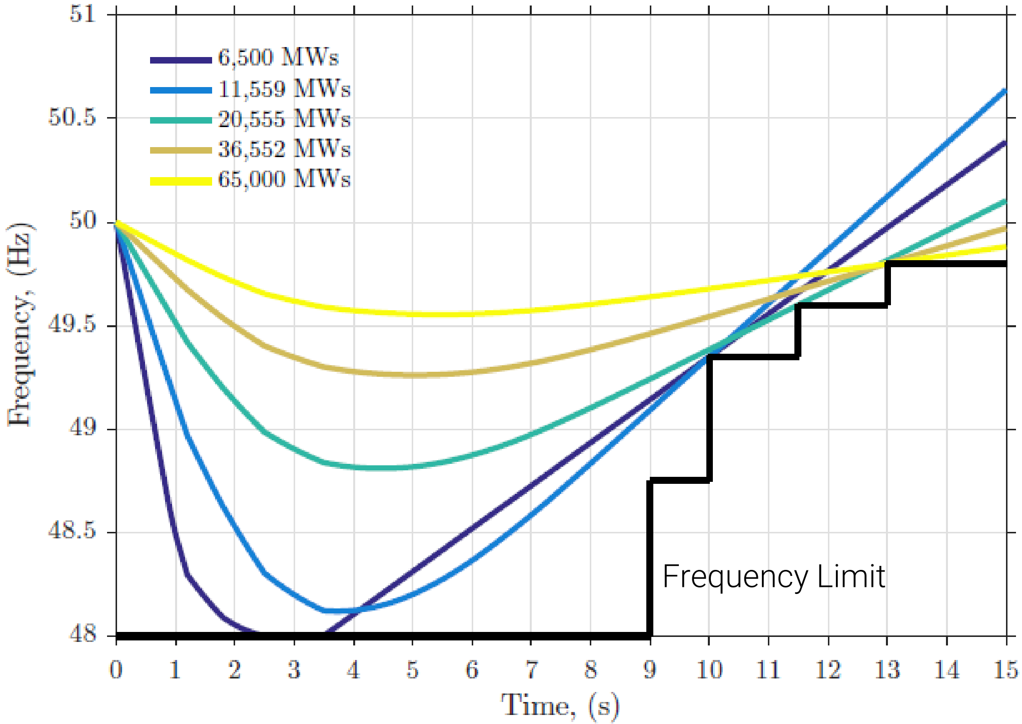
	Quantity (MW)	Price ($/MW)	$t_{i,p}/t_{i,u}$ (s)	g_i (MW/s)
	IL Offers			
1	68	400	0.9	-
2	16	300	1	-
3	54	200	1	-
4	152	160	1.2	-
5	23	120	1.8	-
6	89	80	2.5	-
7	48	0	3.5	-
	SR Offers			
1	71	150	0.6	16
2	26	130	0.8	4
3	67	110	1.1	5
4	62	90	1.2	12
5	165	70	1.6	18
6	47	50	2	6
7	33	30	2.2	3
8	28	10	3	6

Increasing Price

Decreasing Response Speed

Variation in Inertia

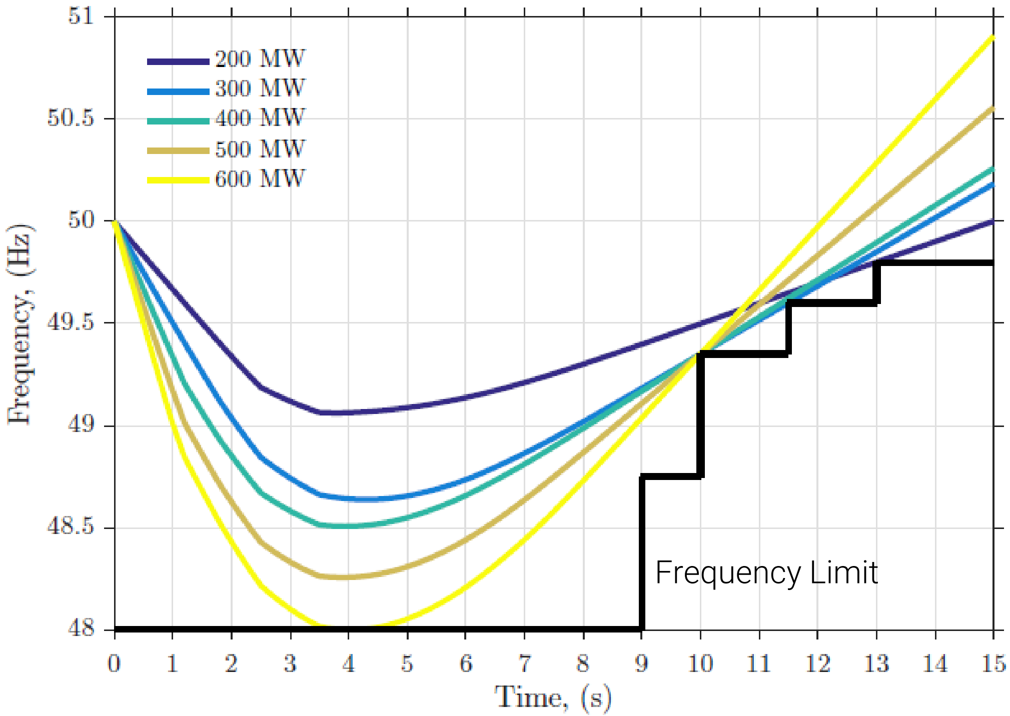
Optimal frequency transient for different inertia on a power system



Risk is 400 MW

Variation in Risk

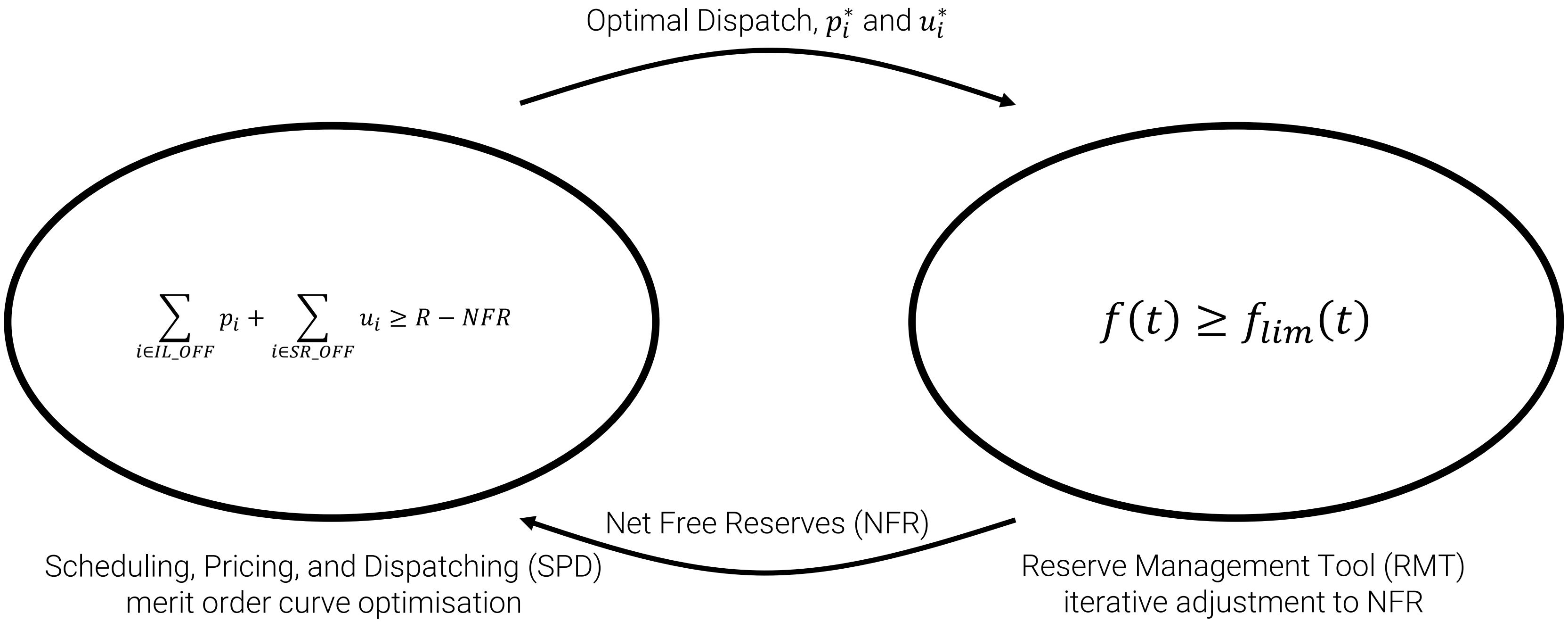
Optimal frequency transient for different risk on a power system



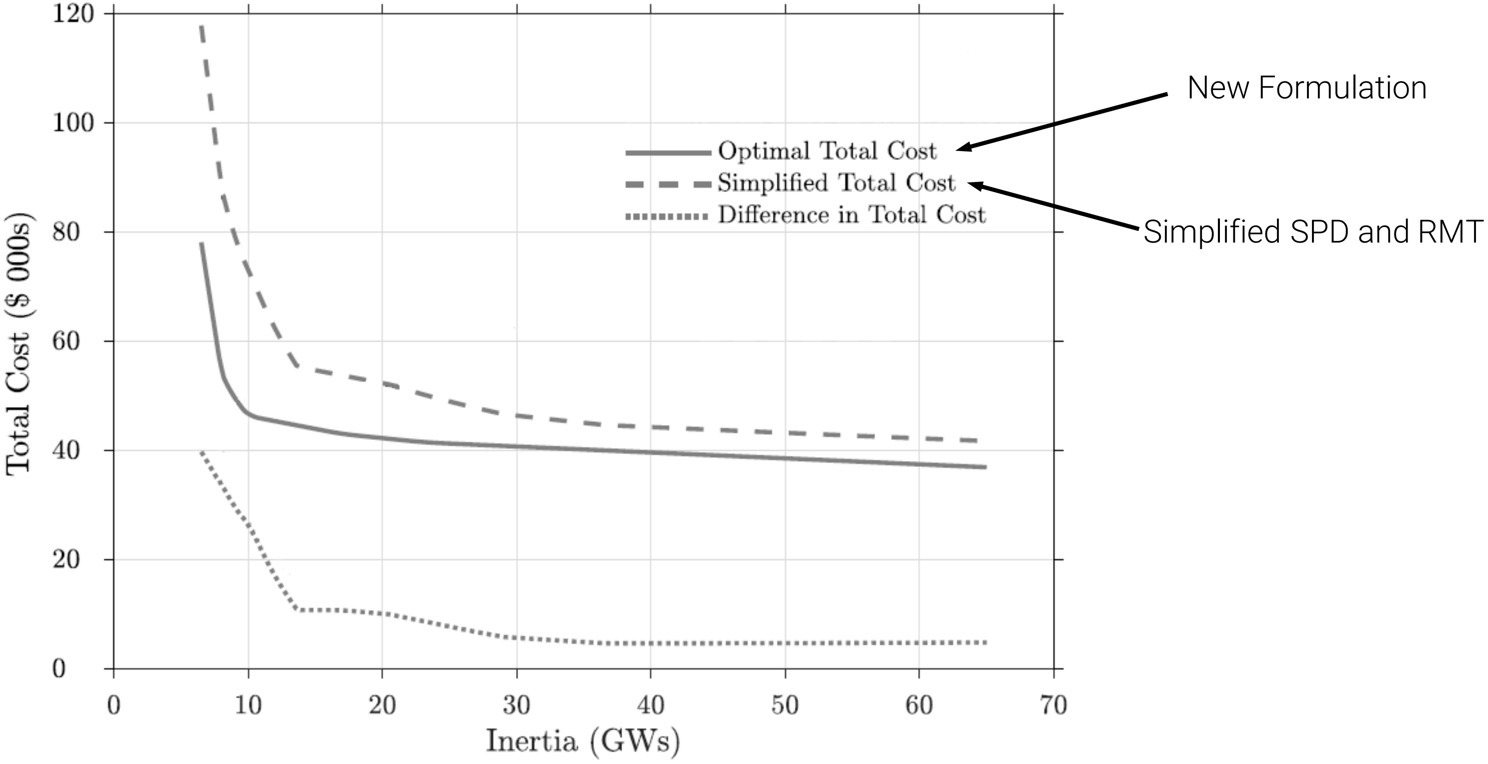
Inertia is 15,000 MWs

Simplified Comparison with Current IR Optimisation

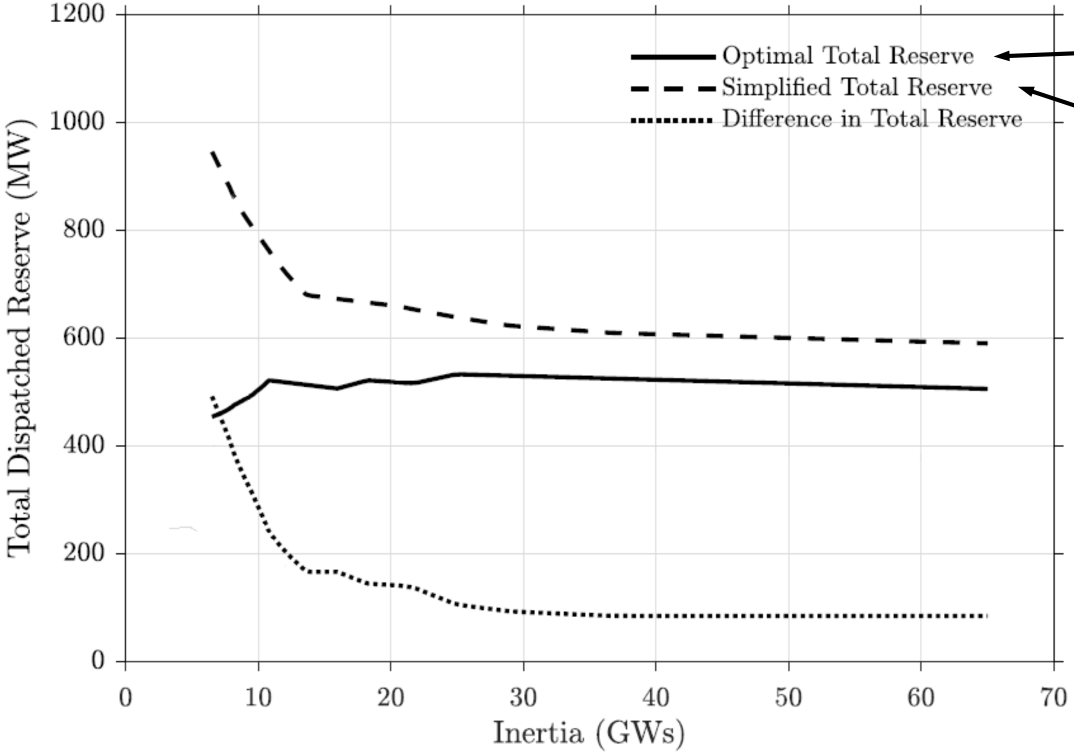
Simplified SPD and RMT Model



Example 2 – Total Cost for Variations in Inertia



Example 2 – Total Reserve for Variations in Inertia



New Formulation

Simplified SPD and RMT

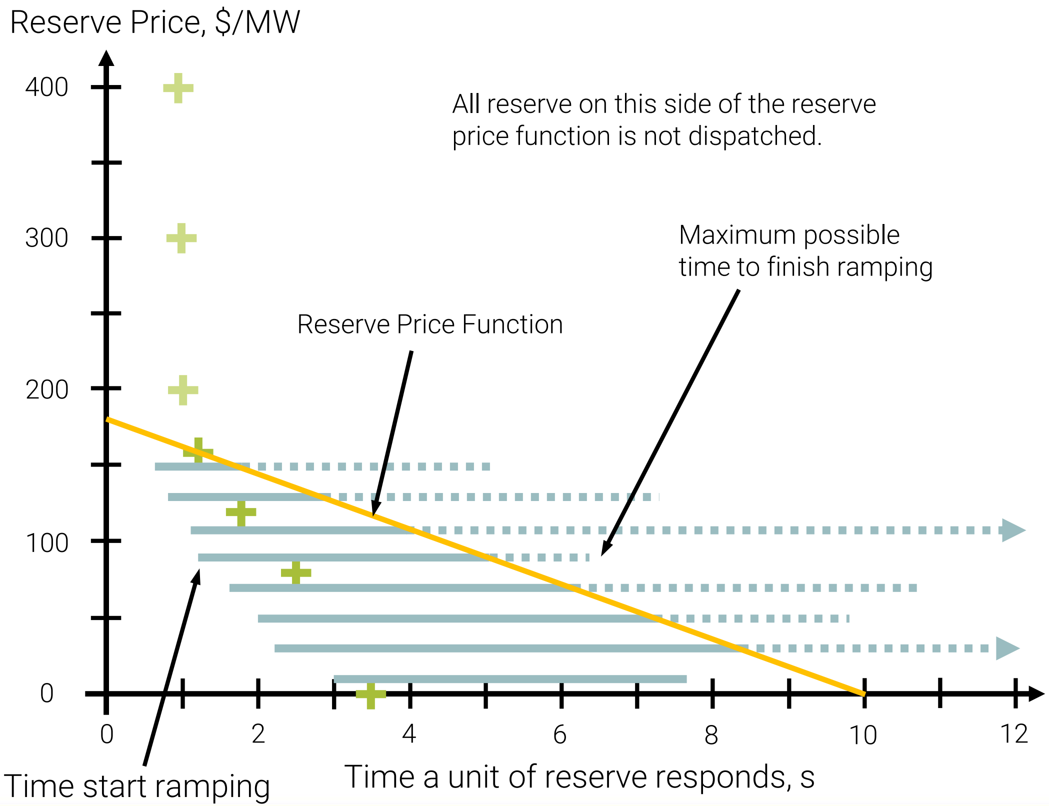
Risk is 400 MW

Pricing Methodology

Comparing Pricing Methodology

- Current Formulation
  - Reserve prices are the shadow price of reserve requirement constraints.
  - Individual prices for Fast Instantaneous Reserve (FIR) and Sustained Instantaneous Reserve (SIR).
- New Formulation
  - Distinction between FIR and SIR is removed.
  - A reserve price function is created instead, a function of time when a unit of reserve responds.
  - The reserve price function is derived from the Karush-Kuhn-Tucker (KKT) conditions.

Example 2 – Dispatched and Undispatched Reserve



	Dispatch (MW)	Quantity (MW)	Price ($/MW)
IL			
1	0	68	400
2	0	16	300
3	0	54	200
4	102.2	152	160
5	23	23	120
6	89	89	80
7	48	48	0
SR			
1	18.4	71	150
2	8.2	26	130
3	14.3	67	110
4	46.2	62	90
5	81.9	165	70
6	31.5	47	50
7	18.5	33	30
8	28	28	10

KKT Condition on Gradients

$$\boldsymbol{c} + \nu \nabla R(\boldsymbol{v}) + \lambda_{min} \nabla F_{min}(\boldsymbol{v}) + \sum_{j} \lambda_{j,l} \nabla F_j(\boldsymbol{v}) - \boldsymbol{\mu}^{min} + \boldsymbol{\mu}^{max} = 0$$

- The vector of optimised variables $\boldsymbol{v} = [H \quad R \quad p_1 \quad \cdots \quad u_1 \quad \cdots]^T$
- The price vector $\boldsymbol{c} = [0 \quad 0 \quad c_{1,p} \quad \cdots \quad c_{1,u} \quad \cdots]^T$
- ν is the KKT multiplier for the reserve requirement constraint $R(\boldsymbol{v}) \leq 0$
- λ_{min} is the KKT multiplier for the minimum frequency constraint $F_{min}(\boldsymbol{v}) \leq 0$
- $\lambda_{j,l}$ is the KKT multiplier for a frequency limit constraint $F_j(\boldsymbol{v}) \leq 0$
- μ_i^{min} is the KKT multiplier for minimum reserve dispatch $p_i \geq 0$ or $u_i \geq 0$
- μ_i^{max} is the KKT multiplier for maximum reserve dispatch $p_i - p_i^{max} \leq 0$ or $u_i - u_i^{max} \leq 0$

Refresher on Gradients – Example

$$\nabla R(\boldsymbol{v}) = \begin{bmatrix} \frac{\partial R(\boldsymbol{v})}{\partial H} \\ \frac{\partial R(\boldsymbol{v})}{\partial R} \\ \frac{\partial R(\boldsymbol{v})}{\partial p_1} \\ \vdots \\ \frac{\partial R(\boldsymbol{v})}{\partial u_1} \\ \vdots \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ -1 \\ \vdots \\ -1 \\ \vdots \end{bmatrix}$$

$$R(\boldsymbol{v}) = R - \sum_{i \in IL\_OFF} p_i - \sum_{i \in SR\_OFF} u_i$$

Frequency Limit Gradient

$$\frac{\partial F_j(\boldsymbol{v})}{\partial H} = 2f_j$$

$$\frac{\partial F_j(\boldsymbol{v})}{\partial R} = t_{j,l}$$

$$\frac{\partial F_j(\boldsymbol{v})}{\partial p_i} = \begin{cases} -(t_{j,l} - t_{i,p}) & \text{If } t_{j,l} \geq t_{i,p} \\ 0 & \text{Otherwise} \end{cases}$$

$$\frac{\partial F_j(\boldsymbol{v})}{\partial u_i} = \begin{cases} -(t_{j,l} - \tau_i) & \text{If } t_{j,l} \geq \tau_i \\ 0 & \text{Otherwise} \end{cases}$$

Where $\tau_i = t_{i,u} + u_i/g_i$

Minimum Frequency Constraint Gradient

$$\frac{\partial F_{min}(\boldsymbol{v})}{\partial H} = 2f_{lim}(t_{min})$$

$$\frac{\partial F_{min}(\boldsymbol{v})}{\partial R} = t_{min}$$

$$\frac{\partial F_{min}(\boldsymbol{v})}{\partial p_i} = \begin{cases} -(t_{min} - t_{i,p}) & \text{If } t_{min} \geq t_{i,p} \\ 0 & \text{Otherwise} \end{cases}$$

$$\frac{\partial F_{min}(\boldsymbol{v})}{\partial u_i} = \begin{cases} -(t_{min} - \tau_i) & \text{If } t_{min} \geq \tau_i \\ 0 & \text{Otherwise} \end{cases}$$

Where $\tau_i = t_{i,u} + u_i/g_i$

Reserve Price Function

- The KKT Condition on the gradients gives the relationship between the reserve price and the time a unit of reserve responds.

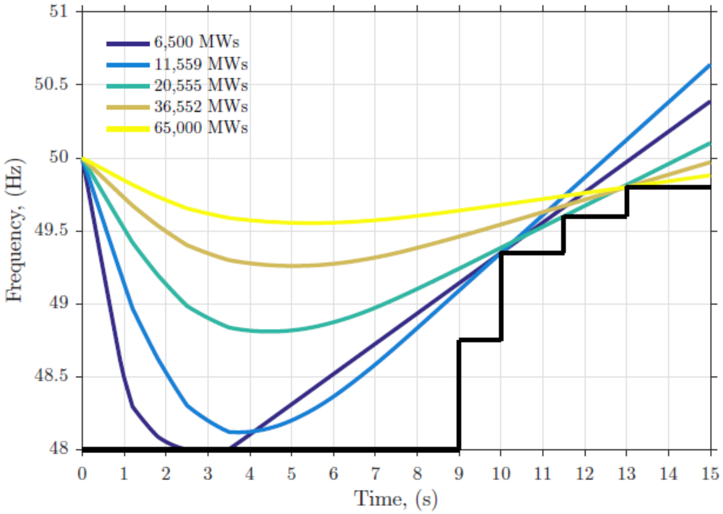
- The Reserve Price Function is

$$c(\tau) = \nu + \sum_{\substack{k \\ \tau \leq t_k}} \lambda_k (t_k - \tau)$$

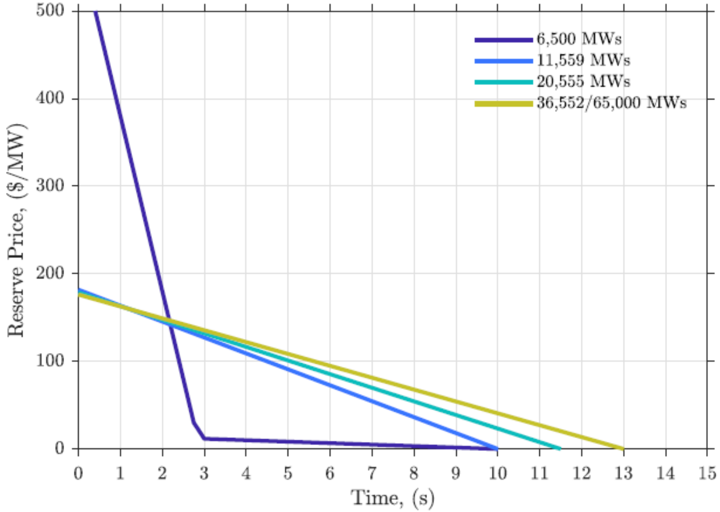
where $\lambda_k \in \{\lambda_{min}, \lambda_{1,l}, \lambda_{2,l}, \cdots\}$ and $t_k \in \{t_{min}, t_{1,l}, t_{2,l}, \cdots\}$

Example 2 –Frequency Transient and Reserve Price Function

Optimal frequency transient for different inertia on a power system



Reserve Price Function for the same reserve optimisation problems



Remuneration of Reserve

- Remuneration is dependent on the time a unit of reserve responds

- Interruptible Load

$$c(t_{i,p})p_i^*$$

- Spinning Reserve

$$\int_{t_{i,u}}^{t_{i,u}+u_i^*/g_i} g_i c(\tau) d\tau$$

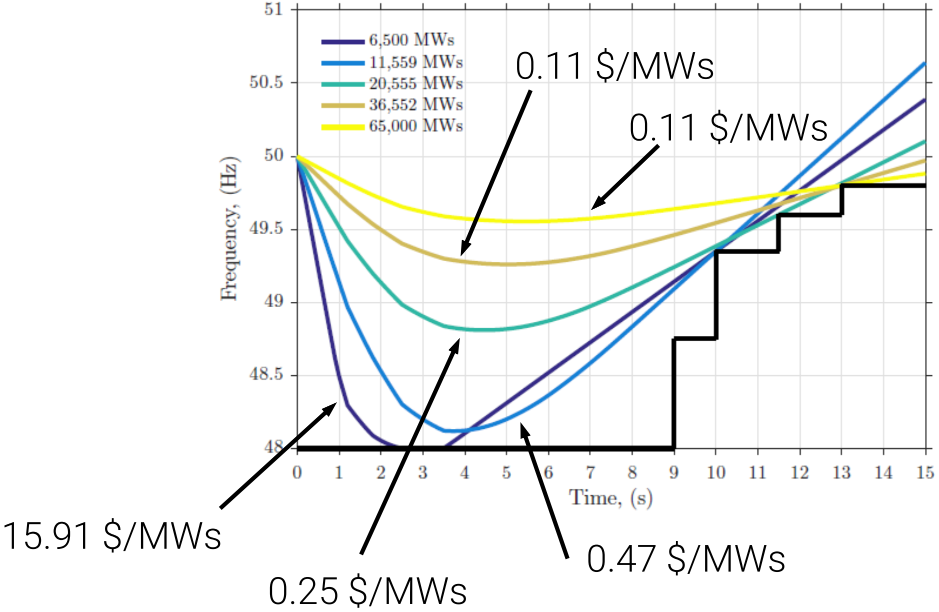
Inertia Price

- The KKT Condition on the gradients also gives an inertia price, c_H.

$$c_H = -2 \sum_k \lambda_k f_{k,\lambda}$$

Where $f_{k,\lambda} \in \{f_{lim}(t_{min}), f_1, f_2, \cdots\}$

Optimal frequency transient for different inertia on a power system



Conclusion

Conclusion

- A new means of optimising reserve for contingencies is presented.
- Which considers response speeds within the optimisation formulation.
- Improves the utilisation of generation and reserve capacity when inertia is low.
- A pricing methodology is developed that is generalised to any positive reserve type.

Thank you to our supporters!

GREEN Grid Programme Supporters

GREEN Grid Premium Funder

MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HĪKINA WHAKATUTUKI

Co-funded by

TRANSPOWER

eea Electricity Engineers' Association

Research Lead

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

EPECentre
ELECTRIC POWER ENGINEERING CENTRE

Research Partner

UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

Centre for Sustainability
Kā Rakahau o Te Ao Tūroa

GREEN Grid In-kind Sponsors

ELECTRICITY AUTHORITY

mainpower

Marlborough Lines

Meridian.

Mitton ElectroNet

networktasman

Northpower

Orion

POWERCO

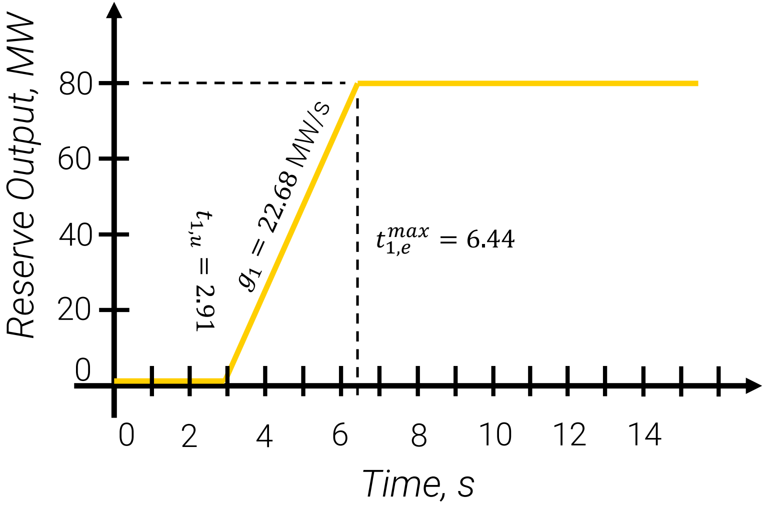
unison

Vector

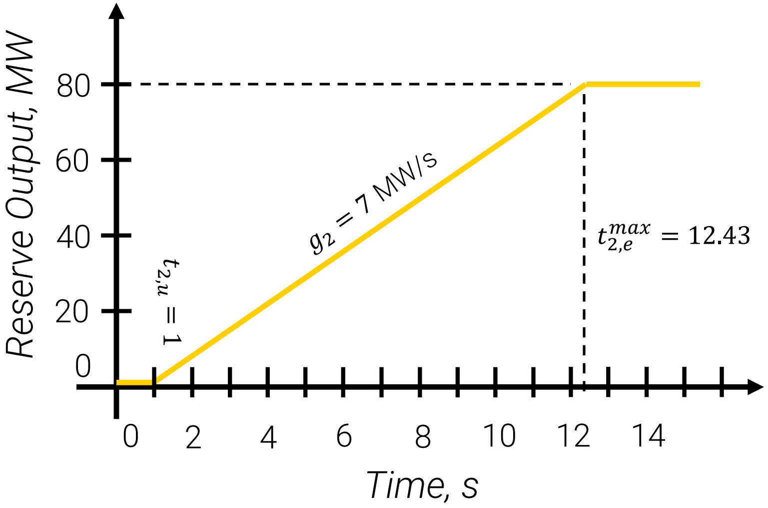
WEL Networks

Simple Example

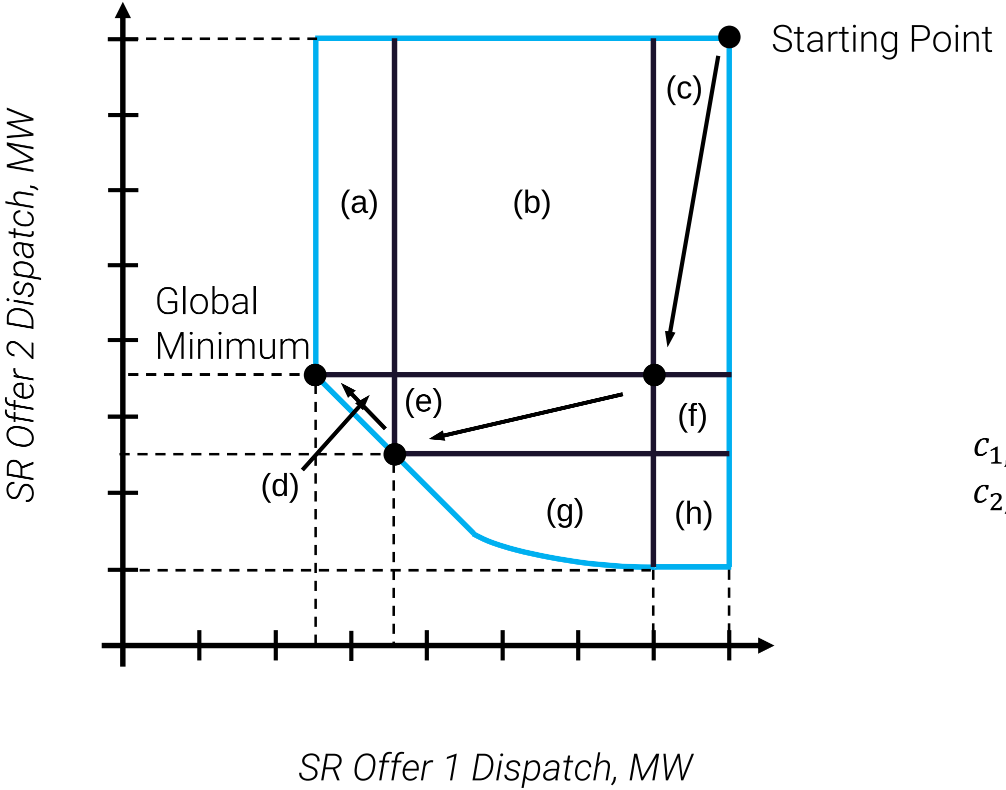
Maximum dispatch of SR Offer 1



Maximum dispatch of SR Offer 2



PQCP Solving

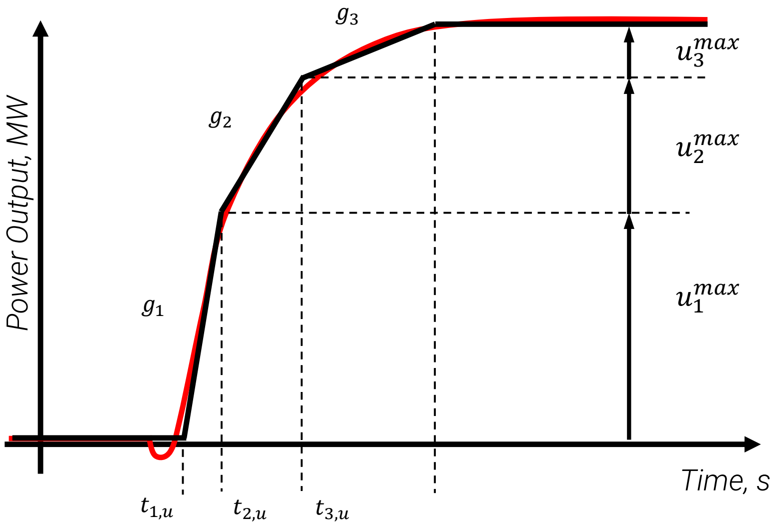


$$c_{1,u} = \$20/MW$$
$$c_{2,u} = \$10/MW$$

Future Development

Modelling Complex Reserve Responses

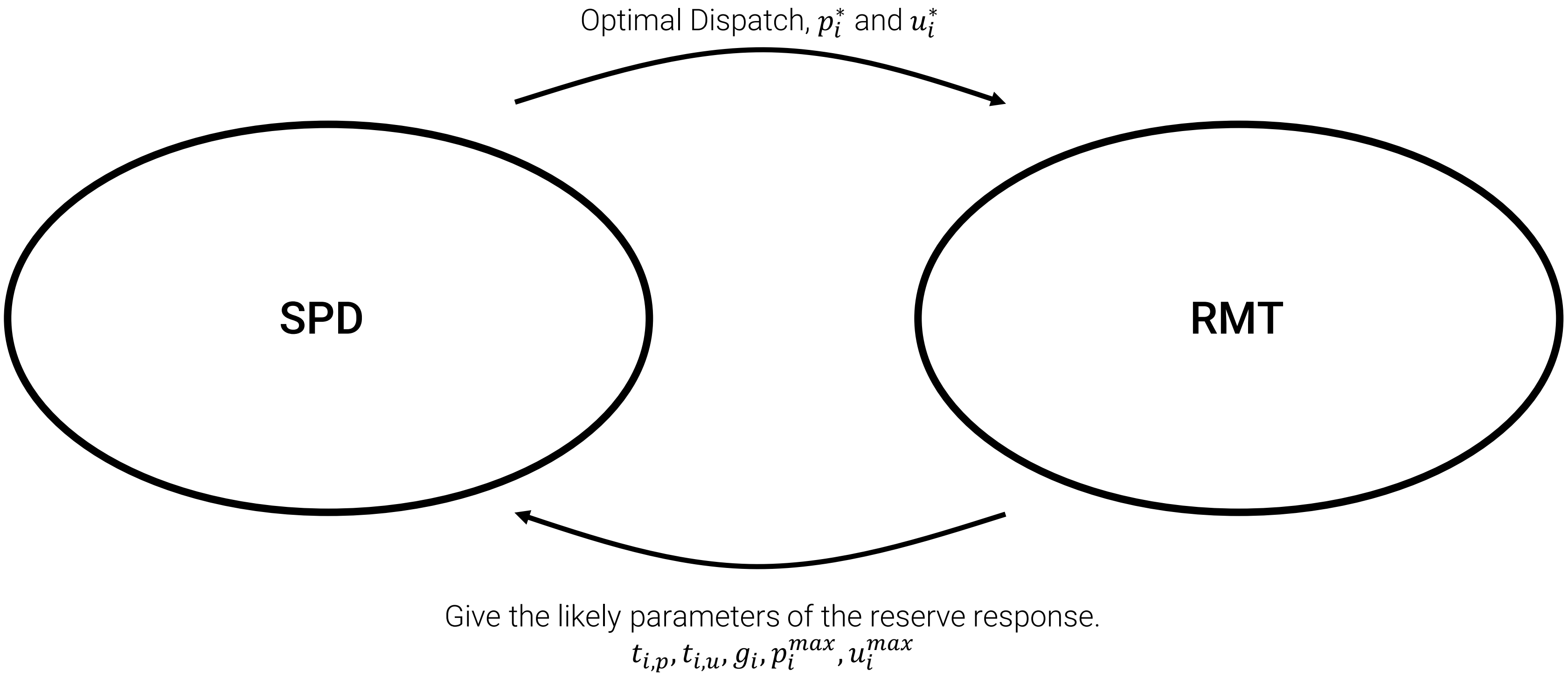
Modelling a Hydro Generator with a step response in desired power output



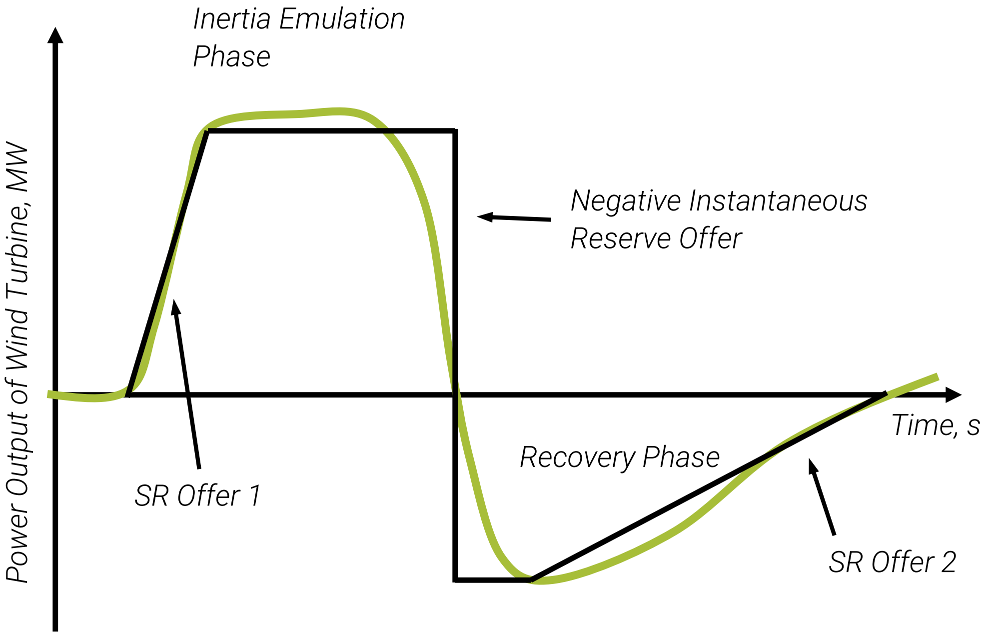
A Mixed Integer PQCP Solver

- Benefits of having a mixed integer version of the solver.
  - Model reserve sharing between the North and South islands.
  - Model the impact of energy generation on the expected reserve response profile.
  - Allow a reserve provider to offer different response speeds.

How would RMT change under the formulation?



Modelling Synthetic Inertia from Wind Turbine



Main challenge of negative instantaneous reserve it is unknown whether the feasible solution space is convex.